Evening Meeting

The meeting was held on 9 October 2008 at IStructE at 18:00h

Structural design and the Eurocodes – a historical review

H. P. J. Taylor
FREng, PhD, CEng, FIStructE, FICE
IStructE Past President, Chair BSI Committee CB/20 Structural Design Codes

C. J. Burgoyne
MA, MSc, PhD, CEng, FIStructE, MICE
Reader in Concrete Structures, University of Cambridge

Keywords: The Concrete Institute, History Codes of practice, Eurocodes, United Kingdom, Reinforced concrete, Design, Plastic theory

On 21 July 1908, the Concrete Institute was formed at a meeting of engineers, architects and others in the Ritz Hotel in London; the Institute later evolved into the Institution of Structural Engineers, which celebrates its Centenary this year. The body has grown from an organisation with 100 members to a body of 22 000 members in more than 100 countries, speaking with authority in the profession of structural engineering.

One of the key objectives of the new Institute was to place, in open record, design rules for the new material, and thus to allow other engineers to apply the new technology. Reinforced concrete had been used for some years before 1908, but it had been controlled by specialist contractors through patents and the retention of experience in-house. In many ways, the development of the professional engineering bodies has mirrored the development of guidelines and codes, the latest of which are the new Eurocodes to be introduced by 2010. These are not just a part of the 'European Project' but have come from a long and continuing process of often contested progress and refinement of engineering practice as well as from political change. The UK has taken a full part in this process.

Codes have developed through an association between the professional institutions, the national legal authorities, academic study and practising engineers, and this process has been reflected in the way that their format and content has emerged. Many of the problems with codes reflect a lack of clarity about what they are for, possibly arising from a lack of appreciation of the requirements of other users. Several groups of people have a stake in codes and with the Eurocodes this has been extended beyond our own national requirements to include those of the other countries involved. This has brought cultural, legal and technical challenges to the authors of the documents.

In this paper we have taken a personal view of the way codes have developed, seeking to point out the importance of parallel developments of structural theory. Our Institution was founded originally as The Concrete Institute and because of this and our personal experience we have followed the history from a concrete design point of view but with reference to other structural materials as parallel developments of their codes took place.

Codes for society

The general public has no idea what codes contain, but know of their existance and rely on their validity. It is a perfectly valid question for a client, whether knowledgeable or not, to ask whether the structure being designed conforms to the latest code. If not, the engineer must be expected to justify why it does not. Thus conformance with a code, although legally optional in the UK, is often regarded as a *sine qua non*. In some countries, on the other hand, the Eurocodes are brought into law. This is an important point to recognise; not only do the Eurocodes have to be used in countries where the engineering culture is different but the position of the codes in law is also markedly different from that in the UK.

Structures are usually freely accessible, bringing a requirement for public safety, which becomes an important aspect of the regulation of construction. Structures are expected to be 'safe as houses'; a bridge collapse attracts public attention out of all proportion to the number of people put at risk, precisely because of its unexpectedness.

Problems clearly arise for the owner of an existing structure when new codes are introduced; if the codes differ, how is the owner to know whether the existing structure should be reassessed? The change to limit state philosophy did not mean that existing structures became inadequate overnight, but other changes, such as a better understanding of loading, or of shear behaviour in concrete structures, may well justify reassessment, strengthening or load limiting.

1

2

Fig 1. Axmouth Bridge – the oldest concrete bridge in the UK / Fig 2. Weaver's Mill, Swansea – the first reinforced concrete building in the UK

3

4

Codes for designers and academics

When one makes a living designing structures, the time taken to carry out a design is clearly important, which can run counter to the needs of the owner of the building who looks for economy of materials and efficiency of the construction process; Society also demands safety and expects durability. A well-written Code should balance these competing requirements. Should codes actually be documents that say 'This is how you design …'?

Construction differs from other branches of engineering in that virtually every structure is unique; each client has their own brief and the physical location of the structure has an impact on the design. Why are motorway bridges not all the same? Every structural design is a prototype, so although engineers gain experience from one project to the next there is not the refinement of design that is possible in other industries where design evolution occurs before the final product hits the market. A generally accepted method of design or Code is clearly important in defining criteria and resolving uncertainties appropriate for this method of realisation.

When engineers in the UK become Chartered Members of an Institution, their ability to combine their knowledge of structural mechanics and practical experience is assessed. The JBM rigorously assesses undergraduate courses and the Institutions quite properly check that applicants are versed in current practice. So in theory we should not need to be told how to design; we already have that knowledge. But it is unrealistic to expect that every engineer knows what to do in all circumstances, and it is one of the commonest complaints to Professional Conduct Committees that 'the engineer worked outside his competence'. So codes do serve a purpose in telling the engineer what limits should apply. But should the codes tell the engineer how to get the answer?

This is a dilemma facing code writers. If the code is to be used by designers of basic structures, which probably covers a large proportion of the work done by many structural engineers, then it is perfectly reasonable to write the code in such a way that it can be read as a design guide. The reinforced concrete codes show this clearly – it is perfectly possible to use the code equations for flexure and shear directly to get both the size of the section and the reinforcement required without, it can be argued, actually understanding what one is doing. But what if you are not designing a simple structure? What if the structure is indeterminate? What are the bending moments? The code writers can't provide a design guide for all circumstances; they must look at underlying principles.

The situation outside the UK may differ, depending on the process of formation of engineers. The UK process requires a combination of academic achievement and tested practical experience, but this is not common in Europe and in many countries, the academic part of formation is extended and the practical 'proof' of competence is reduced. The Eurocodes have been drafted by technical teams with these very different backgrounds and as a result they do not necessarily contain the same compromises between academic content and practical design rules.

The resolution of this dilemma lies in the commentary to the code. It is perfectly feasible for the code itself to embody the underlying principles, while the commentary explains how the code should be used in different circumstances. This is another important role for the Institution, as exemplified by Prof. Nethercot's committee managing the introduction of the codes to the profession, coordinating with professional bodies, industry bodies such as the Concrete Centre, SCI, TRADA and commercial bodies.

Codes for product design

The Construction Product Directive is currently being reviewed and will be published as the Construction Product Regulations. This is an important change as it will introduce the CE marking of structural products to the UK, not as an option but compulsorily. This requires that designed construction products have a common basis of design, the Eurocodes. An important part of the Eurocode suite is the way in which this is integrated with product standards to allow CE marking to proceed. This has not been without difficulty; the Eurocode clauses take precedence but there have been problems with the drafters of product standards not recognising this and exceeding their brief in writing alternative technical material.

An ideal code and commentary

The essential features of a modern design code, and its associated commentary, can be listed as:

- independence of advice;
- up-to-date content;
- putting knowledge of material properties to safe structural use through appropriate structural theory;
- a balance between safety and economy but with no compromise of safety;
- distillation of technical knowledge into simple rules;
- a basis for regulation;
- a support for contract and specification;
- a means of sharing construction expertise;
- a freedom to allow progress and alternative approaches in unusual applications.

In addition Eurocodes also provide:

- A means of ensuring public safety throughout the European Union.

Fig 3. Modern bridge beams push technical limits (*photo: Tarmac*) / Fig 4. Rion-Antirion Bridge, Greece – designed for severe earthquake loading

5

- A means of use for designed construction products which can then be CE marked, thus supporting the Construction Products Directive, now to be replaced by the Construction Products Regulations.
- A means of design for projects required by European Law to be free to competition within the European Union, thus supporting the Public Works and Public Services Directives.
- A basis for International use.

Historical development

Codes were not new to the 100 founders of the Concrete Institute, since building regulations had existed for many years. Records show regulation almost at the dawn of recorded history; in the Babylonian Code of Hammurabi, clauses 228 to 233 directly address building control in a much more ruthless way than we currently require.

Regulations for building control in the UK have been in place for many years. After a large fire thatch was banned in London in 1212. Following the great fire of London of 1666, legislation was passed relating to Building Control which was then actually observed!

It is an interesting coincidence that the excellent fire protection properties of concrete were recognised in 1908 as important and a reason why the stranglehold of the contractors and patent holders should be broken to give way to publicly available design rules. It was also thought important that the properties of structural concrete were described or 'codified' without 'excessive laudation' from contractors' literature!

The work of the Institute was recognised in the London County Council (LCC) Regulations of 1916 and continued in collaboration with The Department of Scientific and Industrial Research (DSIR) in the development of design proposals. The change to the Institution of Structural Engineers took place in 1922 and involvement in codes and standards continued.

In 1908 structural theory relied upon the elastic theory developed from the work of Hooke, Young and Euler, and from knowledge obtained from practical use. From 1660 significant progress had been made with Elastic Theory, which relies upon the proportionality between stress and strain in a linear elastic material. Design was based on determining a safe working stress that a material could sustain, and then through calculation, sometimes backed by testing, ensuring that the stresses at the working load were below this limit with some safety factor.

There were always significant doubts about whether elastic theory should be applied to a material like reinforced concrete, which is designed to crack at the working load so that the tensile forces are carried by the reinforcement. Safety factors were quite high, as can be seen from the excellent performance of structures from the period. Design stresses were low and there was little need to carry out further checks to consider other working load conditions such as deflection and vibration. Factors of safety in fact also included factors of ignorance. This is not the case now; refinement of design can mean a reduction in safety factors and greater economy, but it puts a greater onus on ensuring that the theories are correct.

Plasticity theory

The most important change to structural theory occurred in the 1930s, when it became practicable to measure stresses in real structures through the use of strain gauges. It was observed that the stresses in real steel-framed structures bore little resemblance to the predictions of linear elastic theory; residual stresses from manufacture, lack-of-fit at joints and settlement of supports, all of which are essentially unknowable by the designer, meant that loads were being redistributed within the structure in such a way that made nonsense of the predictions. And yet the structures were still performing well.

It was known that after the limit of proportionality between stress and strain was reached, wrought iron and steel demonstrated 'plastic flow', when increasing strains could be sustained without increasing stress on the 'yield plateau'. Baker used these ideas in his development of the Morrison bomb shelters used inside houses in World War II; they absorbed energy by plastic deformation rather than resisting the force that it generated.

It was less clear that these methods could be applied to concrete, which is a brittle material but, by correct detailing, reinforced structures can be produced which have a ductile yield plateau in flexure, and to a lesser extent, in shear. The ideas had in fact been developed much earlier, by Ingerslev in 1923 and Johanson in 1931, when they analysed concrete slabs. Slabs are infinitely indeterminate and thus difficult to analyse elastically by hand. Yield line methods of analysis were developed which revolutionised the design of slabs since approximate calculations could be carried out by hand.

These ideas were formalised after World War II by the development of 'Plastic Theory' by Hodge, Ducker, Prager and Hill. Structural theory is a three-legged stool, relying on three principles for support: the principle of equilibrium, which says that all forces must balance; the principle of compatibility, in which all the bits must fit together, and a constitutive relationship for the materials that relates the forces to the deformations.

Elastic theory purports to satisfy all three, but is known to be incorrect because it has to make assumptions, mostly about geometric compatibility, that cannot be justified. As an alternative, Plastic Theory was developed which gives bounds on the load capacity of a structure. It relies on two main theorems:

- ***Static (or Lower Bound) Theorem:*** If a set of internal forces are deter-

Fig 5. Modern construction is all about speed – lower floors finished before upper ones started

mined which can be sustained by the structural members and which are in equilibrium with the external loads acting on the structure then the load carried by the structure is a lower bound to the true collapse load. No mention is made of compatibility.

- ***The Kinematic (or Upper Bound) Theorem:*** If a mode of collapse is assumed in which all the deformations are compatible with the external forces causing this condition are an upper bound to the collapse load. No mention is made of equilibrium.

If both are satisfied then the true collapse load has been found, but this is difficult to find and is rarely sought.

Modern codes use plastic methods and the bound theorems to limit the ultimate load capacity of a structure, while retaining elastic methods to deal with stresses and deformations at the working load. In the existing British codes that distinction is buried, and is often overlooked by practicing engineers, but in the Eurocodes the distinction is more obvious.

Computer analysis

The other major change that has occurred is the use of computers to perform analyses. Structural theory, as taught before about 1970, was aimed at finding the force distribution in a structure in the simplest possible way. This involved minimising the number of simultaneous equations that had to be solved and led to techniques where the engineer identified 'the indeterminacies' of a structure and to relaxation techniques such as moment distribution.

Computers have done away with all that. Solving simultaneous equations is no longer difficult, so the degree of indeterminacy of a structure is no longer relevant and the analyst thinks about the number of 'degrees of freedom' that the structure possesses. Solving a thousand or even a million, unknowns is trivial. The suppliers of analysis programs now provide us with easy methods of data entry, and such stunningly beautiful three dimensional plots of stress distributions, that it is easy to lose sight of what has been analysed. These programs make a number of (hidden) assumptions, either to simplify the analysis or because the information is unknown. Materials are often assumed to be linear and elastic, concrete uncracked, supports idealised. There are inherent assumptions; linear or quadratic variations of stress or strain are imposed. None are correct, but what saves the situation is the lower bound theorem, which means that, provided the engineer designs a ductile structure with adequate strength to resist the equilibrium solution determined by the program, the structure will be safe. But how many engineers know that? How do the codes ensure safety? They do it by ensuring ductility, and this is done by detailing rules that make no reference to why they are there.

'Modern' codes

It is now necessary to trace the development of the codes to understand how these advances in theory influenced design practice. Most post-war national codes, such as CP 114 (reinforced concrete) and CP 115 (prestressed concrete) still relied on elastic theory, with its fairly arbitrary 'factors of safety' that gave designers a false sense of security. This was widely held to be unsatisfactory. This and similar concerns of designers elsewhere led to the formation, at an international meeting in Cambridge in 1952, of the Federation International de la Precontraint (FIP). In the following year the Comite Europeen du Beton (CEB) was formed with the objective of international technical collaboration. The first CEB FIP model code for the design of structural concrete was written and published in15 languages in 1964 with a second edition in 1970. FIP and CEB united to form FIB in 1998 and its ground-breaking work continues.

The CEB code introduced Limit State principles to the engineering profession. The aim is to ensure that 'the chance of each limit state being reached is substantially constant for all members in a structure, is appropriate for each limit state and that consequently there is an adequate degree of safety against the structure being unfit for use.' Serviceability limit states are defined (the structure should not deflect too much at the working load) as are ultimate limit states (the structure should not collapse until a higher load is reached). Limit state codes can take account of the different variabilities of various materials and loads (concrete is more variable than steel; highway loads are more variable than hydrostatic pressure), and also the consequences of failure (nuclear power stations should have higher factors of safety than conventional buildings). The model code ideas were taken up in the writing of the first UK limit-state code CP 110, *The Structural use of Concrete*. The UK steel code, the composite and masonry codes changed to a limit state format quite quickly afterwards. Codes new to the limit state format are the Eurocodes for timber and geotechnics.

The theoretical aim of the limit state process is that working load and ultimate performance can be verified by the use of the theories of probability. Unfortunately, structural failure results more often from human error than from the intersection of the extreme ends of the frequency distributions for load and strength. Attempts at deriving fully probabilistic methods of structural design all ultimately rely upon calibration, comparing the theoretical conclusions with existing design methods and practice.

When the European Commission was looking for a means of writing a set of European Codes to support its free market initiatives, it was natural to use the pan-European achievement of the CEB and similar organisations. The program was first run by the Commission but the responsibility for writing and publication was transferred to CEN, the European Standards Body by special agreement in 1989.

How are our standards written? Essentially they are written by experts, in the past entirely voluntarily, but increasingly now standards are written by experts supported by a combination of industry and public finance. British Standards are published by the British Standards Institute, (BSI) itself a venerable institution with over 100 years of history. The national standards bodies, working through CEN, have collaborated by providing experts, who carry no national brief but are selected purely on the basis of their expertise and who have written the Eurocodes. A set of CEN rules have been written which define the process for production and which cover areas such as timing, consultation, technical review, national vote, translation and publication. As a result, the 10 Eurocodes comprising 58 parts are all now complete and in each country a further series of National Annexes are being prepared to feed in the safety factors, the choice of which is derogated to the individual nation states, and other material where agreement could not be found in the committees. The next step in the future will be to maintain the codes and work towards full harmonisation of all of the design parameters.

What do Eurocodes mean?

Eurocodes are not just some average of the different national codes that existed before. There is a move away, partially but not completely, from the old 'deemed to satisfy' philosophy of the old UK codes.

It will become even more important that engineers properly understand not only the structural mechanics involved but also its limitations. The stresses produced by a modern analysis may bear no better relation to the assumptions made by the designer than they did when the first measurements were made in the 1930s, and for the same reasons. Many properties are unknowable and construction effects incalculable; engineers will continue to rely on the Lower Bound Theorem and ought to understand it.

The future

Eurocodes are not the end. The existence of National Annexes has no technical justification. Physics is, fortunately, the same everywhere so if a structure is safe in Greece it ought to be safe in Scotland, given the European ideal that standards of construction are uniform. Loading codes may need geographic criteria to allow for variations in seismicity or wind loading, but the strength factors should not change. One of the next tasks is to move towards the elimination of recommended values and national choice. This project has already started with the collection of all of National Annexes from all of the member states. Achieving unanimity in this area will take time.

There is also a question about new developments. The structural use of glass and of frp are at a stage where design activity is at the point of moving from the work of a few experts to the main body of the profession. Germany has already put forward a proposal for a Eurocode on the structural use of glass which BSI will support, while FIB is working on a model code for frp in concrete.

It remains important that the structural engineering profession remains based in a proper understanding of the underlying principles, and sees the codes for what they really are.

When one considers the different engineering cultures that exist in Europe, the forms that construction takes, the different ways in which Building Control is carried out in practice, the progressive enlargement of the European Union, which took place while the documents were being drafted, and all of the other differences, loyalties and prejudices, the Eurocode achievement is considerable.

The Eurocodes are not just a product of the political will to unite Europe in trade but should be seen as the current stage of progression of structural engineering theory and practice which will continue to develop as construction changes to serve us all.